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The research we have done has shown that effective saccadic control is achieved by a division of labor between high-level mechanisms that select targets and plan scanning strategies, and low-level mechanisms that bring the line of sight to the center of attended regions and adjust saccade metrics by means of adaptive control. Understanding these processing and programming tricks is valuable for designing tasks and displays that produce best-possible performance, for developing models of the human visual, motor and cognitive systems, and for improving the design of robotic and other systems that, like human beings, must acquire information sequentially from large and complex visual scenses, with only a limited processing resources.

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Eye Movements and Visual Information Processing

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Publications (1996-2000, includes work submitted and in preparation during period of grant listed above)

Epelboim, J., Steinman, R.M., Kowler, E., Pizlo, Z., Erkelens, C.J., and Collewijn, H. (1997) Gaze shift dynamics in two kinds of sequential looking tasks. Vision Research, 37, 2597-2607.

McGowan, J., Kowler, E., Sharma, A. and Chubb, C. (1998) Saccadic localization of random dot targets. Vision Research, 38, 895-909.

Bahcall, D.O. and Kowler, E. (1999) Attentional interference at small spatial separations. Vision Research, 39, 71-86.

Kowler, E. (1999) Eye movements and visual attention. In: MIT Encyclopedia of Cognitive Science.

Melcher, D. and Kowler, E. (1999) Shape, surfaces and saccades. Vision Research, 39, 2929-2946.

Bahcall, D.O. and Kowler, E. (1999) Illusory shifts in perceived visual direction accompany adaptation of saccadic eye movements. Nature, 400, 864-866.

Bahcall, D.O. and Kowler, E. (2000) The control of saccadic adaptation: Implications for the scanning of natural visual scenes. Vision Research, 40, 2779-2796.

Vishwanath, D., Kowler, E. and Feldman, J. (2000) Saccadic localization of occluded targets. Vision Research, 40, 2797-2811.

Invited talks:

Kowler, E. "Shifts of attention and eye movements" (symposium speaker) Neural Control of Movement meeting. Cancun, April, 1997.

Kowler, E. "Saccadic eye movements and attention". Symposium: Pre-Attentive and Attentive Mechanisms in Vision (3rd annual Vision Research Conference, Ft. Lauderdale, May, 1999).

Conference presentations:

McGowan, J., Kowler, E., Sharma, A. and Chubb, C. (1996) Precise saccadic localization of random dot targets. Investigative Ophthalmology and Visual Sciences Supplement, 37, S524.

Melcher, D. and Kowler, E. (1998) Shapes, surfaces and saccades. ARVO (May 1998)

Vishwanath, D., Kowler, E. and Feldman, J. (1998) Saccadic localization of occluded targets. ARVO (May 1998)

Description of accomplishments:

Saccadic eye movements are indispensable for gathering information from visual scenes. In order for saccades to be an efficient scanning tool, they must bring the line of sight to chosen locations quickly and accurately. If saccades depended exclusively on low-level visuomotor mechanisms to determine each saccadic endpoint, accuracy and speed would be achieved at the expense of voluntary selection of targets. Too much reliance on volition, on the other hand, risks overburdening the cognitive resources needed for evaluating the contents of the scene. The research we have done has shown that effective saccadic control is achieved by a division of labor between high-level mechanisms that select targets and plan scanning strategies, and low-level mechanisms that bring the line of sight to the center of attended regions and adjust saccade metrics by means of adaptive control. Understanding these processing and programming tricks is valuable for designing tasks and displays that produce best-possible performance, for developing models of the human visual, motor and cognitive systems, and for improving the design of robotic and other systems that, like human beings, must acquire information sequentially from large and complex visual scenes, with only a limited processing resources.

Specific accomplishments and current work in progress are as follows:

<u>High-level target selection</u>: It is generally assumed that people choose where they are going to look according to a rational plan, looking at locations where they are likely to find important information that helps them make decisions about what is in the scene and helps them plan behavior. However, the rules for making these decisions are not understood. Two factors need to be taken into account: One is the likelihood of finding useful information at any given location. The other is any constraints on looking patterns that might be imposed by the oculomotor system itself (i.e., the costs). In other words, some sequences of movements might be easier to execute than others. We constructed a very simple search task that incorporated both variations in the likelihood of finding useful information and possible oculomotor constraints. The subject was required to find a target (a letter T) and report its orientation. The T was embedded in a cluster of extraneous targets so that it would not be recognizable unless subjects were looking directly at it. There were two of these clusters, one located to the left and the other to the right of fixation. We varied both the distance of each cluster to fixation and the probability that the T would be found in each cluster. (Probabilities were either .8 for one cluster and .2 for the other; an intensity cue was used to signal probability.) Trials lasted only 500 msec. We expected subjects to look at the location most likely (80%) to contain the T. This strategy, when followed, produced almost perfect performance. Surprisingly only one of the 6 subjects tested used this strategy consistently. Others tended to either look at the nearest location first, regardless of probability, or look always in one direction first. Subjects also often tried to look at both locations, even though there wasn't enough time in the trial to complete this task.

Why didn't the subjects follow the rational strategy of looking at the more probable location? Our results suggest that the costs of following this strategy in terms of the difficulty imposed on oculomotor programming mechanisms was too high. A more convenient strategy included: (1) favoring near locations; (2) pre-planning more than one saccade at a time, (3) planning an overall scanning strategy that minimized total distance travelled.

The results suggest that there may be habitual or built-in scanning preferences and that these may at times preclude people from finding important information quickly. (Araujo, Pavel, and Kowler, in progress).

Saccades and attention: We have previously shown that saccades require shifting a small amount of attention to the chosen target (Kowler et al., Vision Research, 1995). The link between saccades and attention makes programming easier because saccades will be automatically drawn to regions of interest and separate attentional decisions for perception and motor control are not required. In follow up experiments, now underway, we are exploring the link between saccades and attention for different display geometries to better understand the nature of the attentional system that is linked to saccades. In particular, we are finding that certain display geometries lead to significant saccadic mislocalizations if attention is directed elsewhere. The results are so far consistent with the view that attention is distributed over space and that the saccade, once triggered, is drawn to the center of the attended region. Thus, there is a single attentional filter but there are two mechanisms underlying saccadic programming, one determining where the saccade will land and the other when it is triggered. Understanding the saccade/attentional links and their relationship to display geometry is important for designing displays that permit the most rapid and efficient scanning and for designing computer algorithms for robotic control that can simulate the procedures used effectively by human beings (Kowler, Niculescu, and Dosher, in progress).

Related experiments have shown that attention to a single location is accompanied by a impaired perceptibility of nearby locations. This result was controversial because it argues for a local center-surround organization of attention instead of a broad attentional "window". The center-surround organization is useful in reducing the potentially distracting influence of nearby unimportant stimuli and helping observers confine processing regions to the selected target. (Bahcall and Kowler, 1999a).

Saccadic localization: We have been investigating characteristics of saccades to spatially-extended targets. This is important because naturally occurring targets are large yet saccades must land at a single location. We have found that saccades to spatially-extended targets are surprisingly precise (SD of landing positions comparable to those found with small point targets). The precision applies to targets composed of random dots and to targets forming recognizable shapes. Landing position is not biased by the presence of internal textural detail, indicating that the shape as a whole is the most important factor. Obscuring part of the target with occluders is quite harmful in that saccades are unable to accurately locate the completed shape despite sufficient cues to do so. These results are consistent with the idea that saccadic localization is controlled by a spatial pooling process operating over selected shape information to quickly and accurately compute the landing position. This process is only partially amenable to voluntary adjustment of landing position. This result is important again because design of displays requiring fast, accurate scanning should include sufficiently vivid and unoccluded shape information to optimize saccadic accuracy (McGowan, Kowler, Sharma and Chubb, 1998; Melcher and Kowler, 2000; Vishwanath, Kowler and Feldman, 2000). Studies in progress are examining saccadic localization with a variety of 2D and 3D shapes to get a better understanding of the algorithm used to determine landing position, i.e., does it simply average over a proscribed area or is it biased by the presence of important local features?

Saccadic adaptation: Accurate saccades are known to require an adaptive system that monitors accuracy trial by trial and makes overall corrections to factors such as saccadic gain if a consistent pattern of saccadic errors occurs. One series of experiments we have completed examined possible sources of the error signal. We found that contrary to the prevailing assumptions, error is not determined by the actual offset of the saccadic landing position from the target. We dissociated error from offset by a variety of manipulations, including using large targets and also asking subjects to deliberately make saccades a portion of the way to the target. At present the most likely error signal is based on a comparison of the landing position (i.e., the contents of the upcoming foveal image) predicted on the basis of the planned saccade with the landing position (i.e., foveal image) obtained. The difference in these signals is then attributed to saccadic errors contributed by low-level programming mechanisms. (Bahcall and Kowler, 2000)

An unexpected related result supported this view. We found that saccadic adaptation was accompanied by a novel illusion. Subjects had to compare the location of targets flashed right before and right after saccades. Before a period of saccadic adaptation, they could accurately align the targets, showing that there was accurate information about how much the eye had moved. But after adaptation the targets were misaligned by an amount equal to the extent of adaptation, showing that the perceptual system is unaware of the adaptive shifts. This result bears on the classical question of the source of the "efferent copy" signal used for perceptual localization and shows that the signal is drawn from a high level of generation of the motor command. The result also is consistent with the idea that there is a dissociation between intended and actual saccades. Such a dissociation may play an important role in the control of adaptation itself. Understanding the nature and source of the efferent copy signals is important both for ensuring accurate location of targets and for ensuring accurate saccades. (Bahcall and Kowler, 1999b).